The NASA Lightning Nitrogen Oxides Model (LNOM): Recent Updates & Applications

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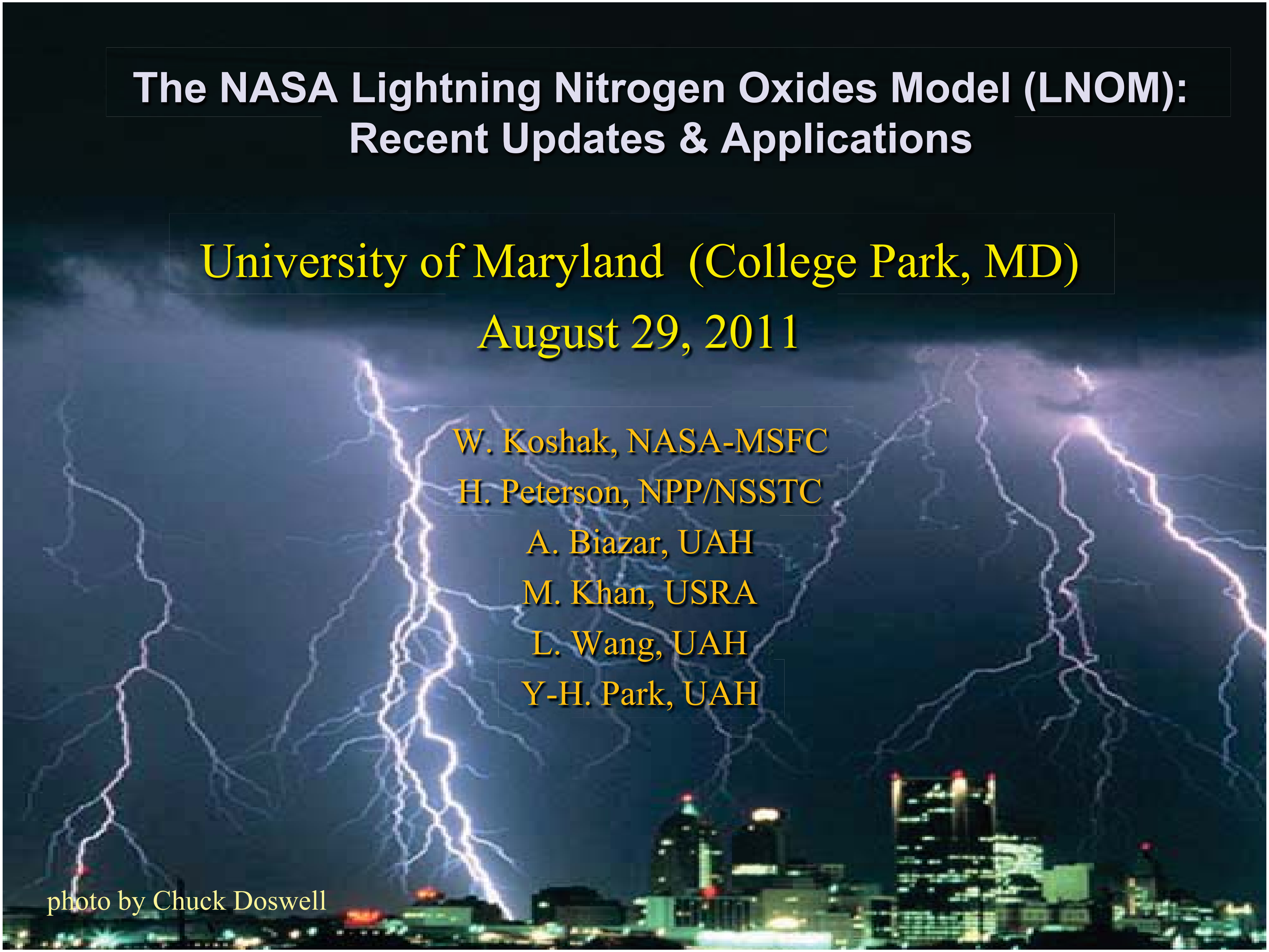


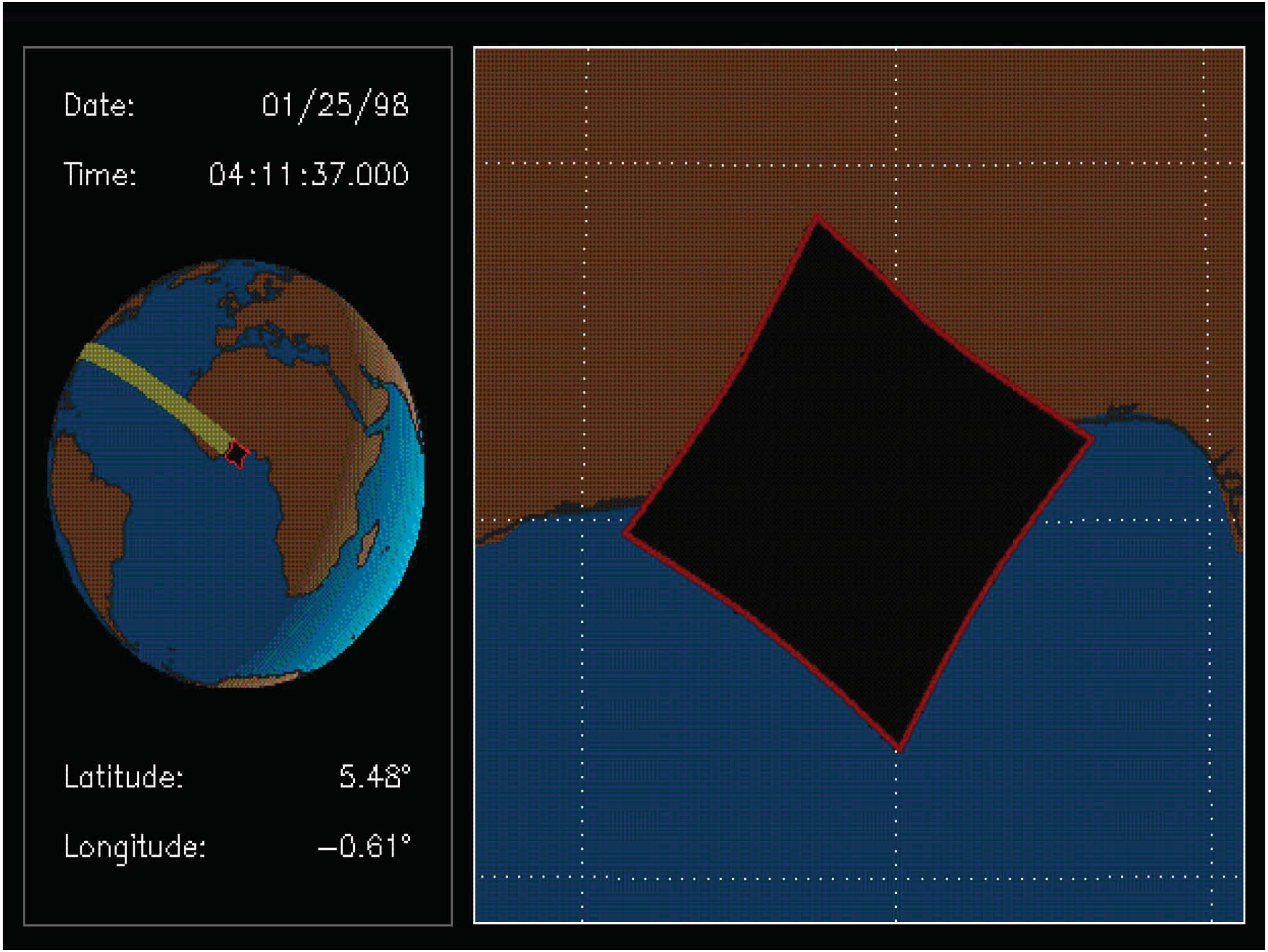
photo by Chuck Doswell

Space Shuttle Video (STS-48)

OTD & LIS

1995-2000

1997-Present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Time: 04:11:37.000
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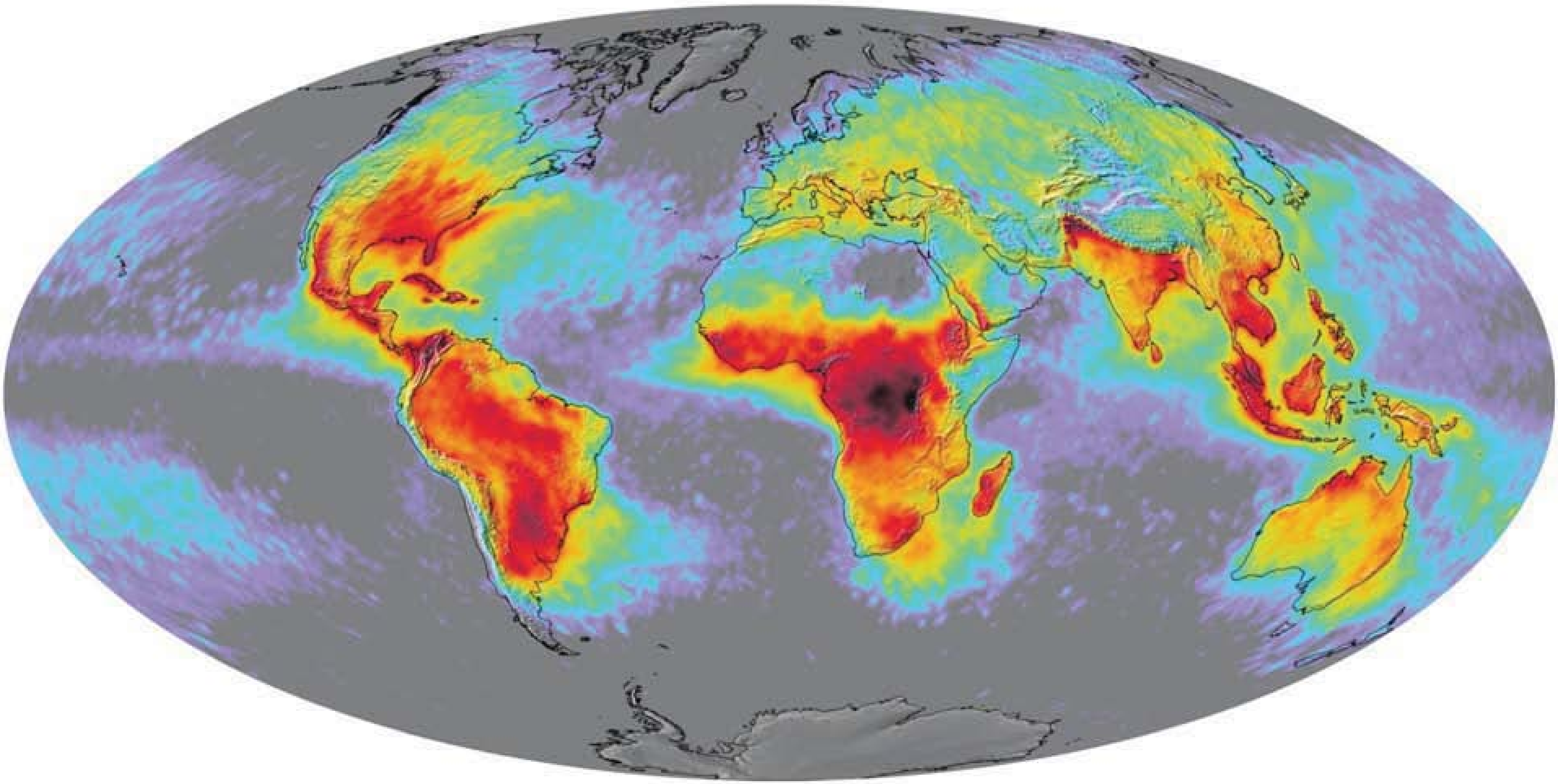
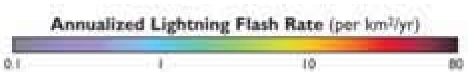
Longitude: –0.61°

Global Distribution of Lightning Activity





Goodman et al., 2007. Our Changing Planet: The View from Space, M. King, ed., Cambridge University Press

Mean annual global lightning flash rate (flashes km^{-2} yr^{-1}) derived from a combined 8 years from April 1995 to February 2003. (Data from the NASA OTD instrument on the OrbView-1 satellite and the LIS instrument on the TRMM satellite.)

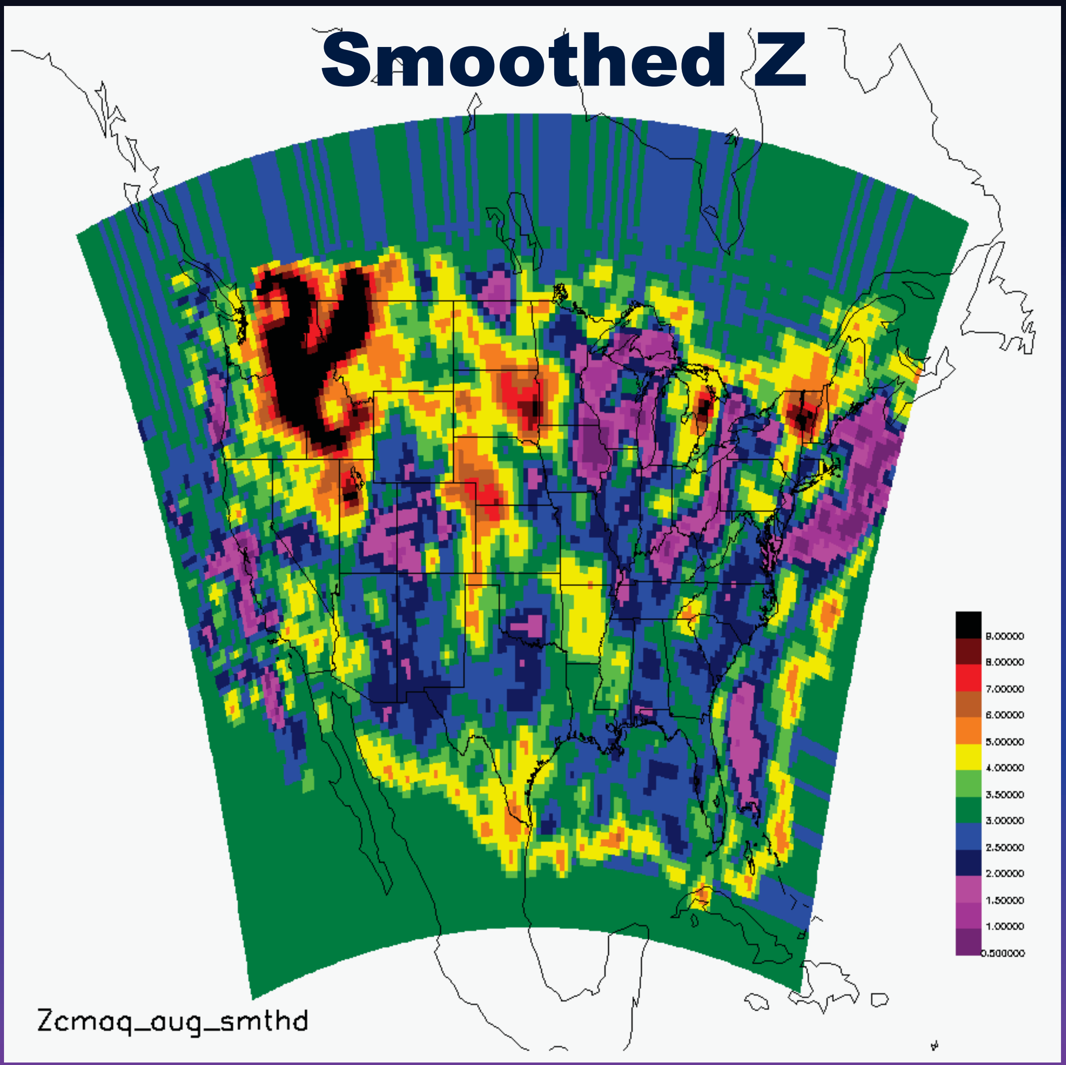
Correlating OTD with NLDN

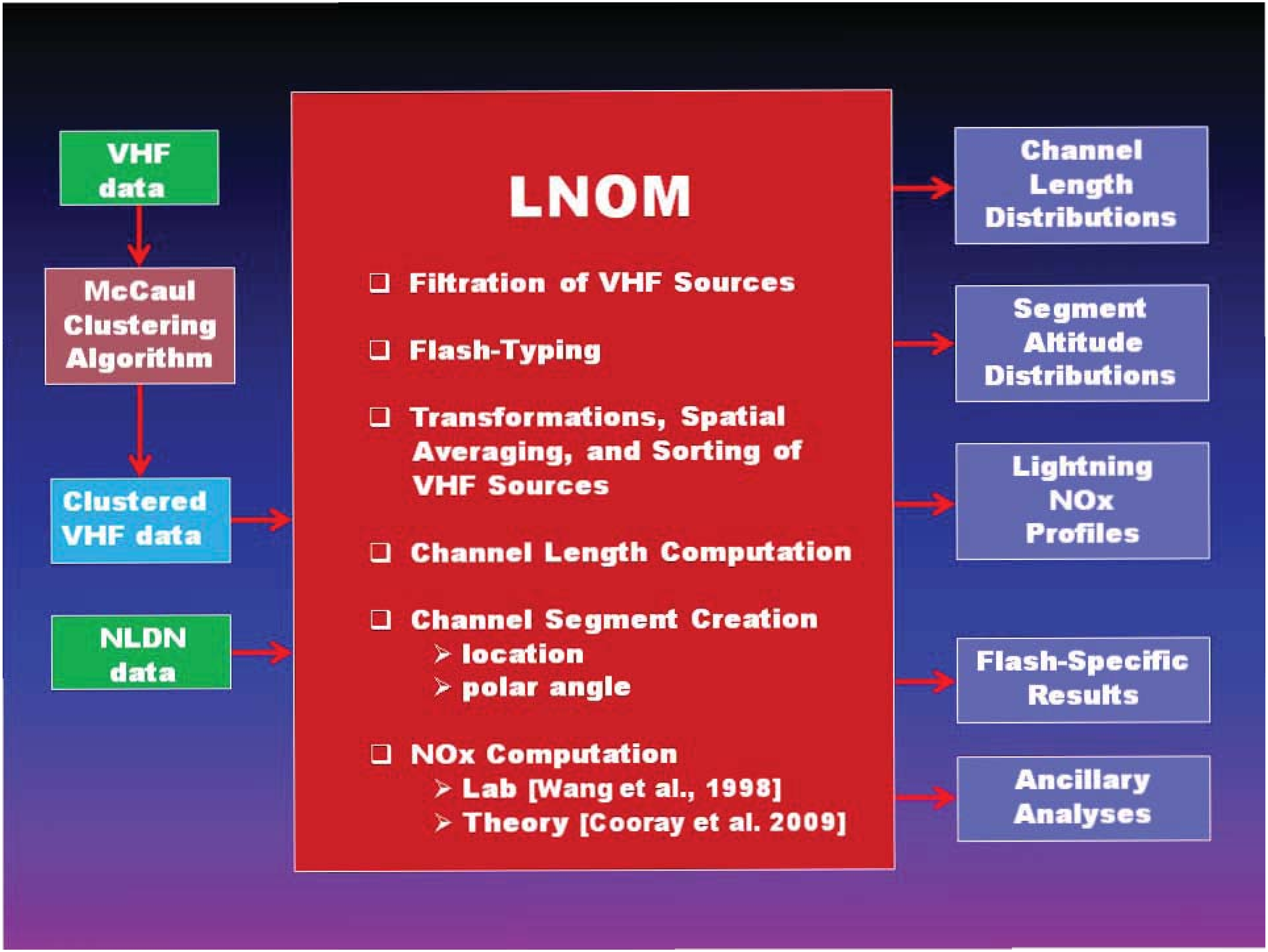
Filling CMAQ Grid Cells with Flashes

- ✓ Get N_g = # CGs from NLDN
  (every hour of each day for each CMAQ cell)

- ✓ Get August Z ratios:
  - extract from 4 year (Boccippio et al. 2001) data base.
  - missing values assigned to 3
  - average (0.5° Boccippio Cell)
  - transfer to CMAQ cells
  - smooth

- ✓ $N_c = ZN_g$ = # Cloud Flashes




VHF data
McCaul Clustering Algorithm
Clustered VHF data
NLDN data
LNOM
Filtration of VHF Sources
Flash-Typing
Transformations, Spatial Averaging, and Sorting of VHF Sources
Channel Length Computation
Channel Segment Creation
location
polar angle
NOx Computation
Lab [Wang et al., 1998]
Theory [Cooray et al. 2009]
Channel Length Distributions
Segment Altitude Distributions
Lightning NOx Profiles
Flash-Specific Results
Ancillary Analyses

NALMA Network

LNOM
Analysis
Cylinder
(vertical extent
is 0-20km)

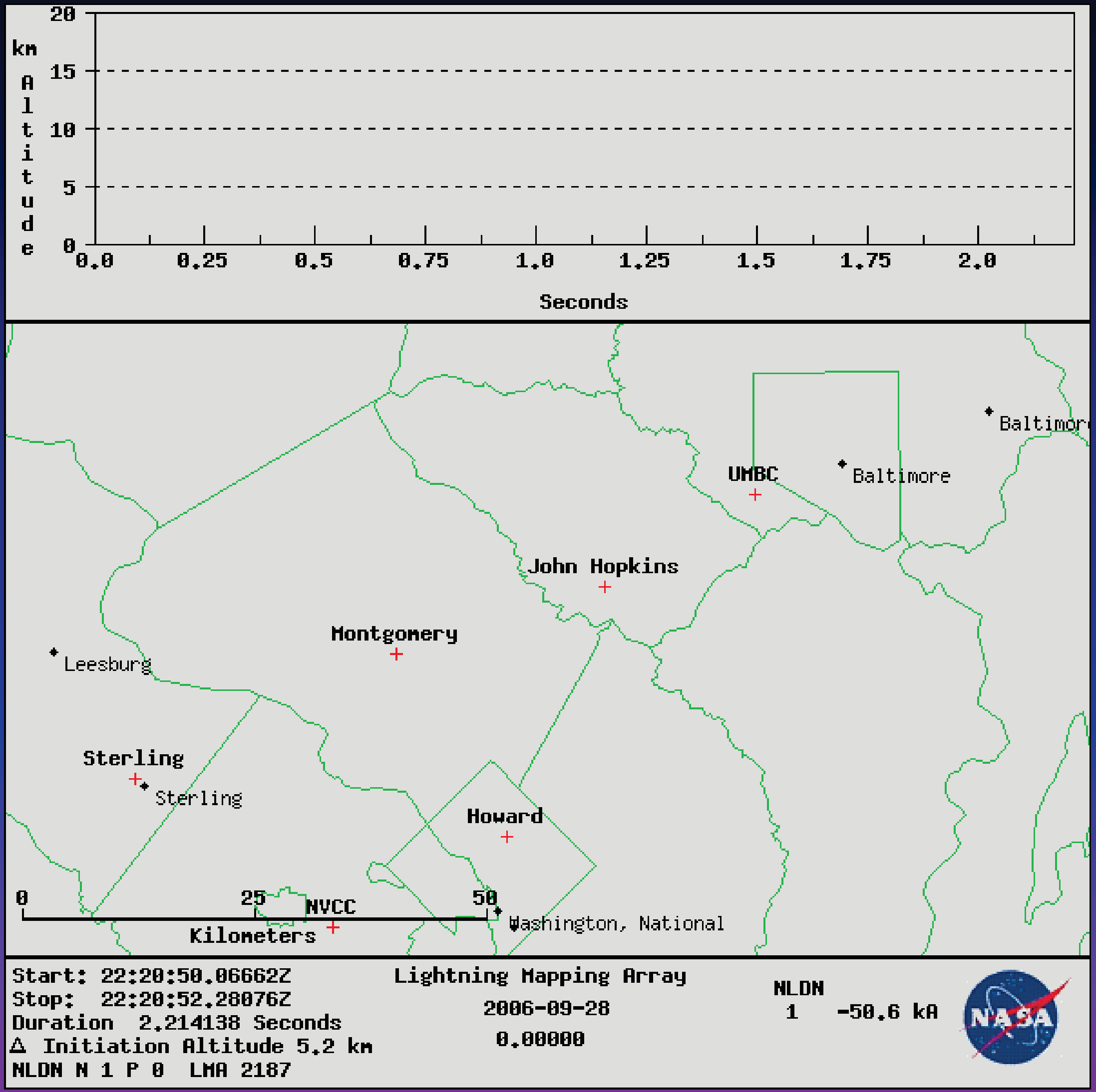
Mimics a
CMAQ grid
volume.

Examine all
flashes in
cylinder for
August
2005-2009.

Router

DC Area Lightning Discharge- Animation

- **2.2 sec hybrid flash**
- **50 km horiz extent**
- **Initiation at 5.2 km**
- **VHF Sources 2187**
- **CG strike at 2 s**

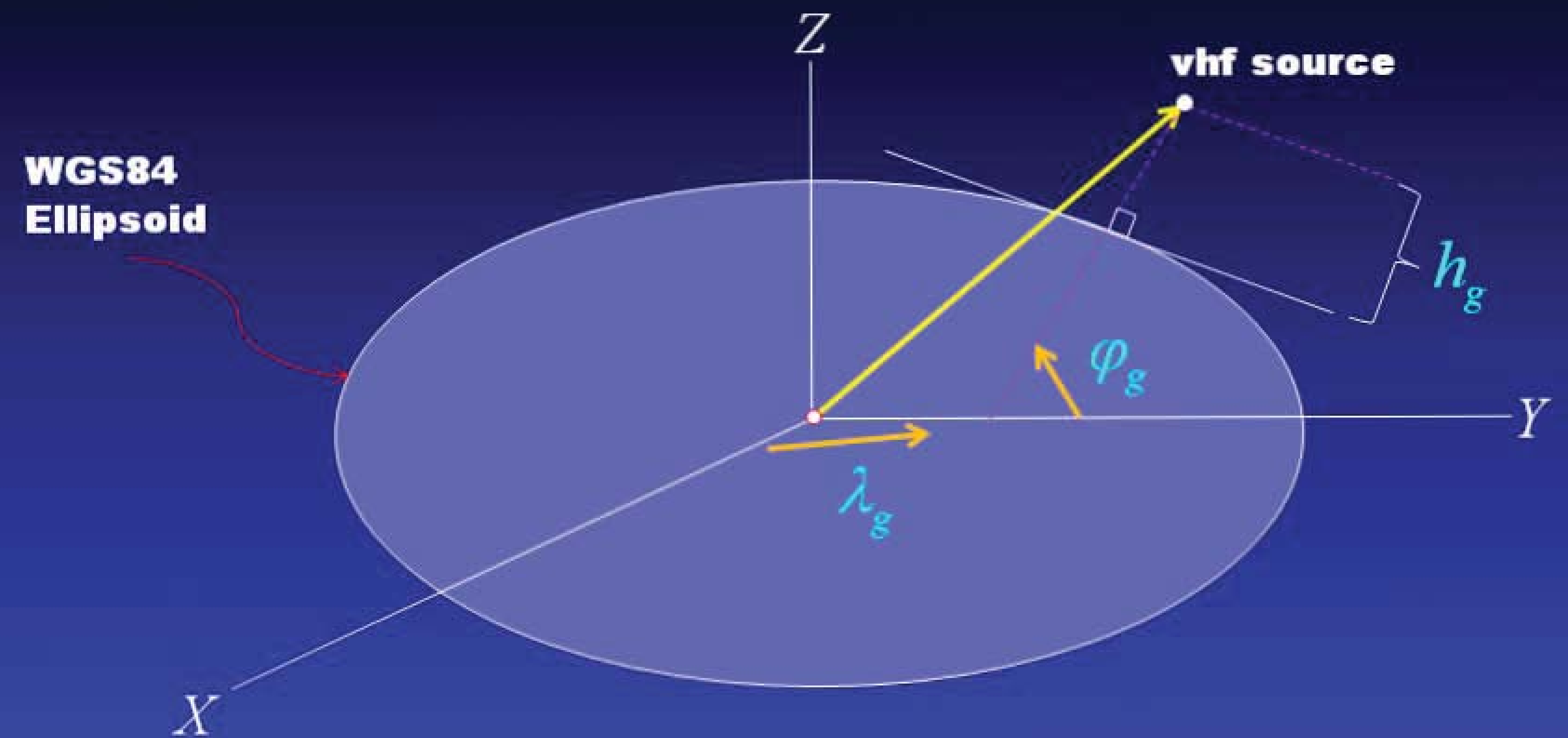


Animated gif

Preprocessing Steps

1. **McCaul Clustering Algorithm**
   - ✓ Ingests LMA data
   - ✓ Only consider vhf sources with chi-square of 2 or less
   - ✓ Cluster these high quality vhf sources into "<u>Things</u>"
     - Things are: Flashes, Small (Non-lightning) Discharges, Noise
   - ✓ Send output files of clustered data to the LNOM
2. **Thing Filtration**
   - ✓ Range Filter (remove if closest vhf source outside cylinder)
   - ✓ Number Filter (remove if it has <20 vhf sources... e.g., singletons)
   - ✓ What remains: legitimate flashes that are at least partially in cylinder
3. **Additional VHF Source Filtration**
   - ✓ Power Filter (remove vhf source if power < 1dbw)
   - ✓ Altitude Filter (remove vhf source if at sfc or >=20km)
4. **Flash-Type Categorization**
   - ✓ Deemed a CG if a NLDN detection is within (100 ms, 10km) and lowest altitude vhf is below N-Region.
5. **Processing of Filtered VHF Sources**
   - ✓ Coordinate Transformation
   - ✓ Spatial Averaging
   - ✓ Sorting

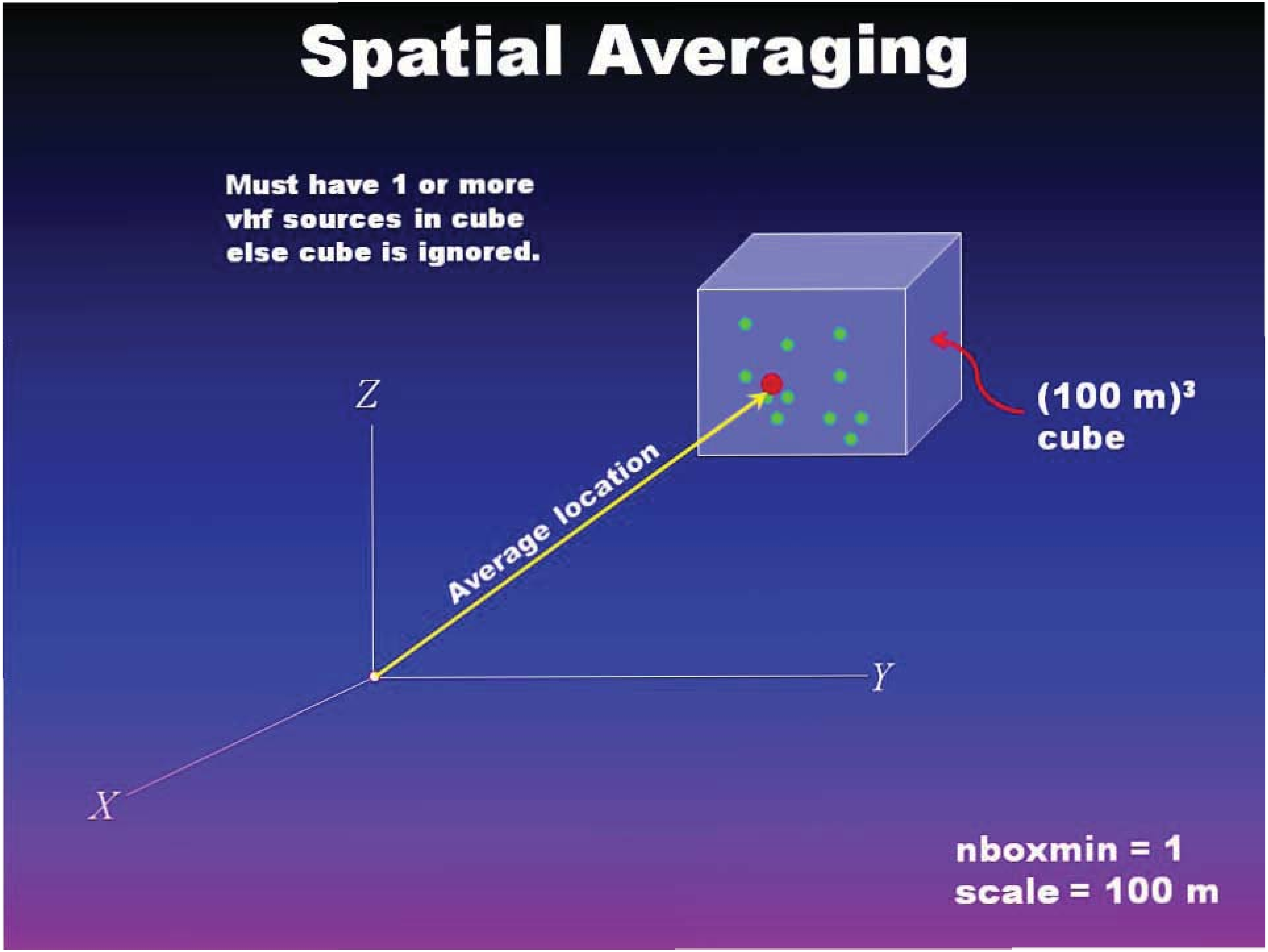
Coordinate Transformations



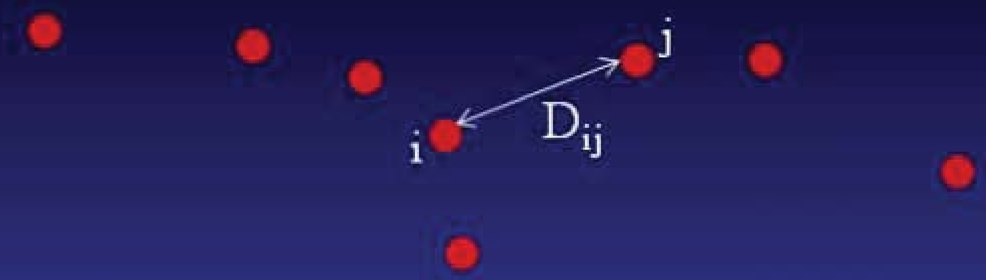
Geodetic $\leftrightarrow$ ECEF

Standard: $(\varphi_g, \lambda_g, h_g) \rightarrow (X, Y, Z)$

Heikkinen (1982): $(\varphi_g, \lambda_g, h_g) \leftarrow (X, Y, Z)$


Spatial Averaging
Must have 1 or more
vhf sources in cube
else cube is ignored.
Z
Average location
(100 m)³
cube
Y
X
nboxmin = 1
scale = 100 m

Channel Length Algorithm

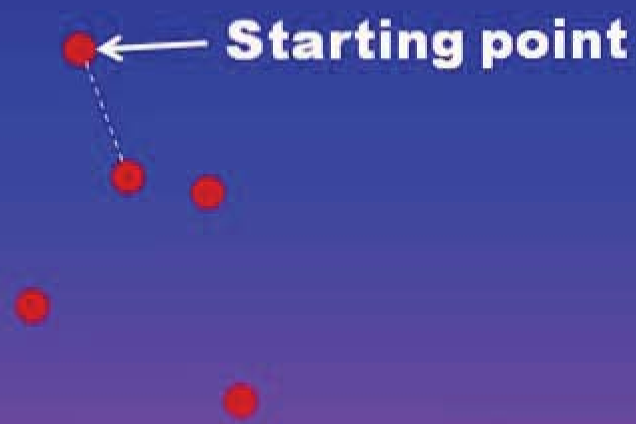


- Compute all the distances between each averaging point (each cube has 1 averaging point, unless the cube was ignored)
- Store each distance, D_{ij}, between ith and jth averaging point in matrix D.
- At this point, note that D is traceless & symmetric
- Assign any element of D that is < 0.1 m to a very large number

Channel Length Algorithm (cont.)

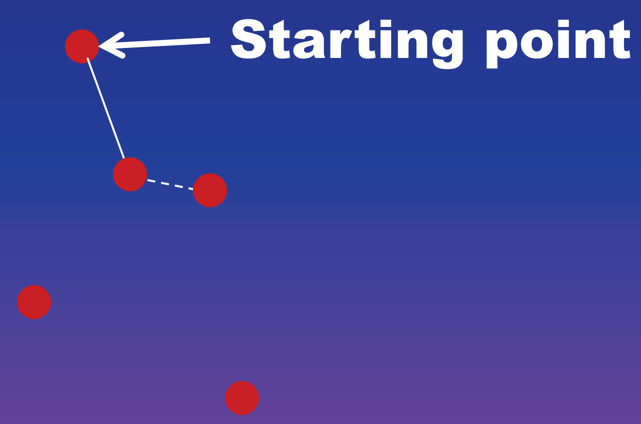
- Begin with n averaging points.

- 1st Iteration:
  - Start at the highest altitude point. Define it to be "on the channel", and all other points to be "free" (off channel).
  - Draw line from starting point to closest free point. This is the first channel "section".
  - Now there are 2 points on the channel, and n-2 free points



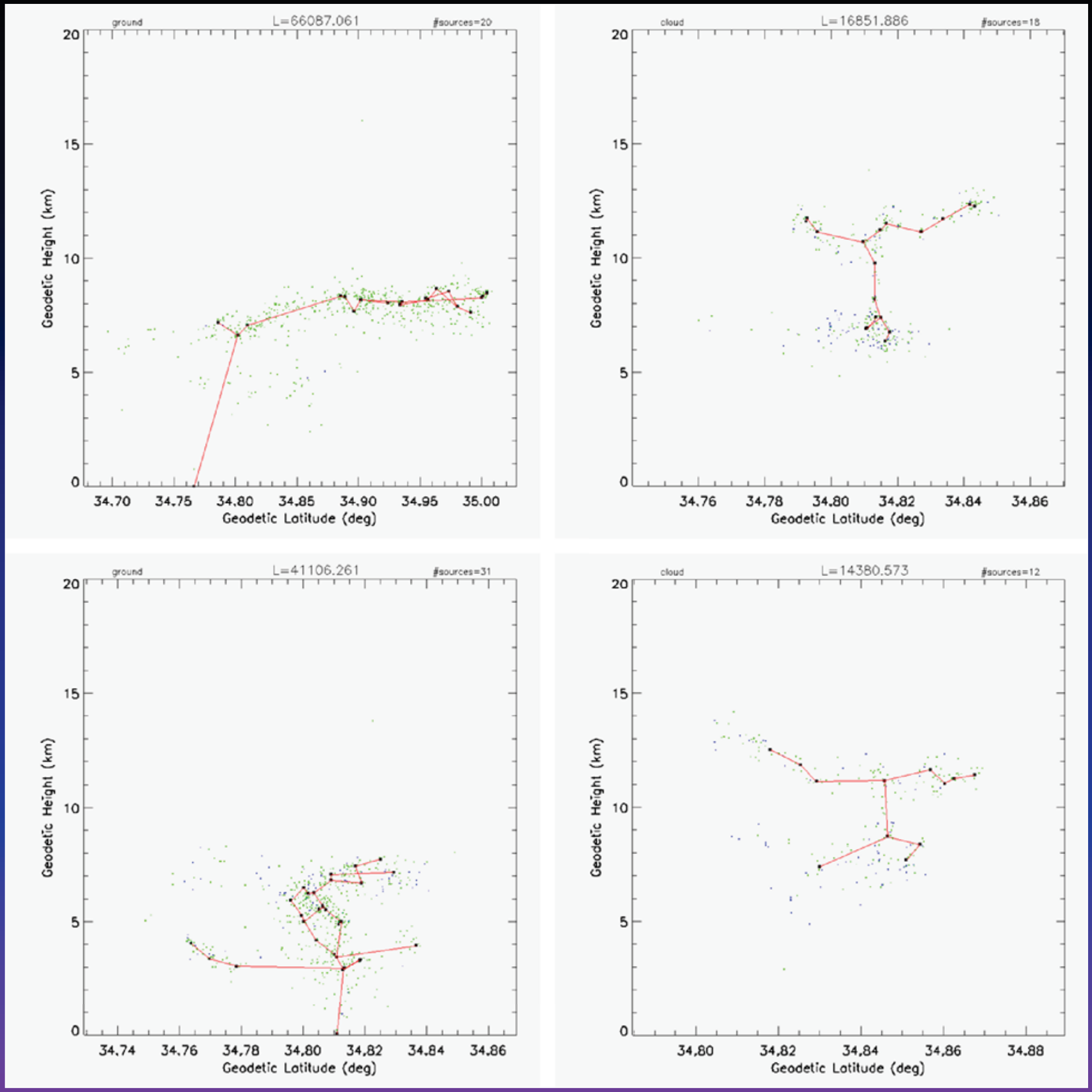
Channel Length Algorithm (cont.)

- **2nd Iteration:**
  - **Find closest free point to 1st channel point**
  - **Find closest free point to 2nd channel point**
  - **Pick min of the mins (i.e., draw line from a free point to a channel point that is the minimum distance).**
- **Continue with more iterations until no more free points**



Sample LNOM Channel Construction

(Aug 2006)



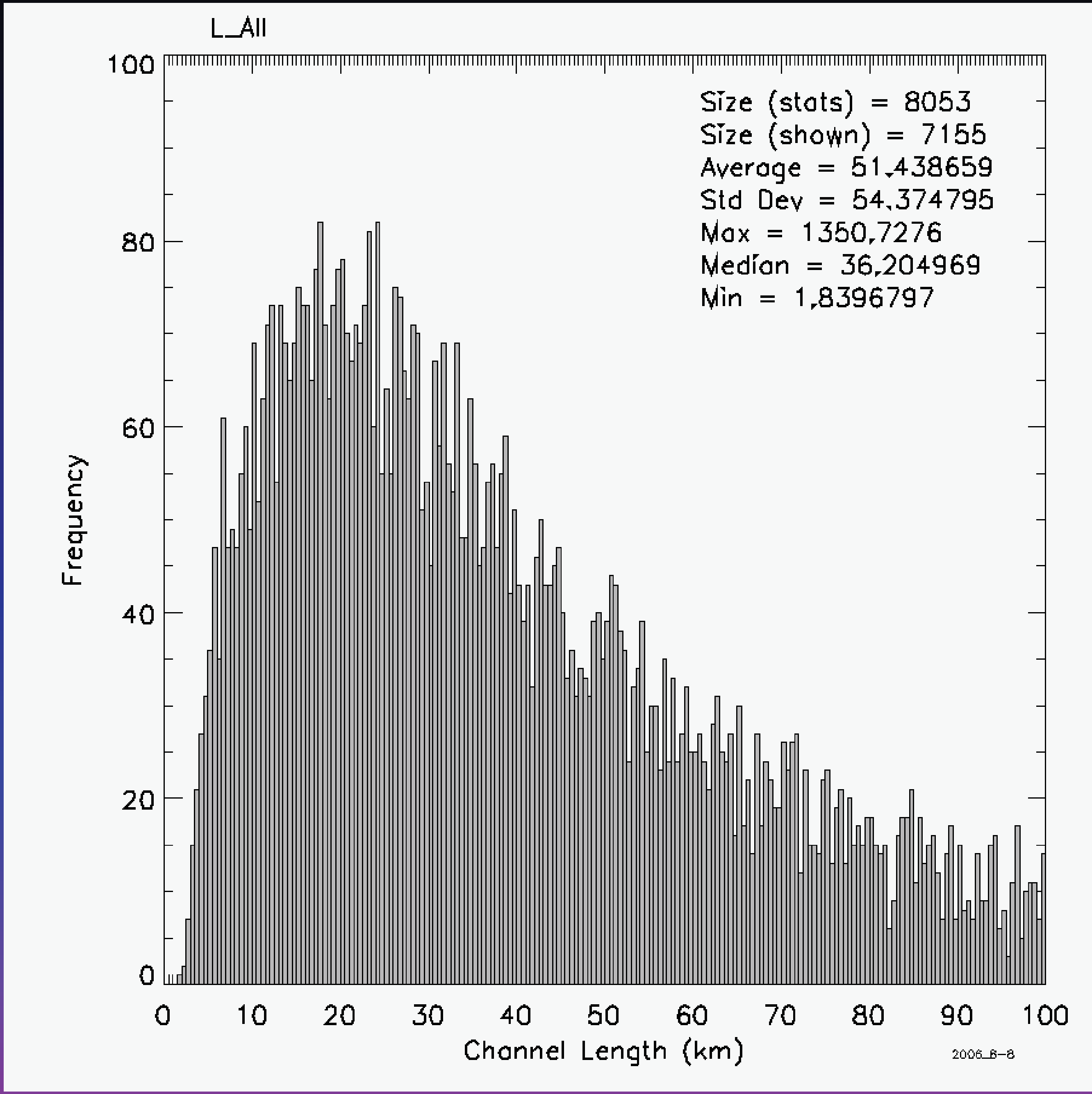
Results shown are for:
- **nboxmin = 5**
- **scale = 1000 meters**

Recent improvements to LNOM now provide more channel resolution than shown here:

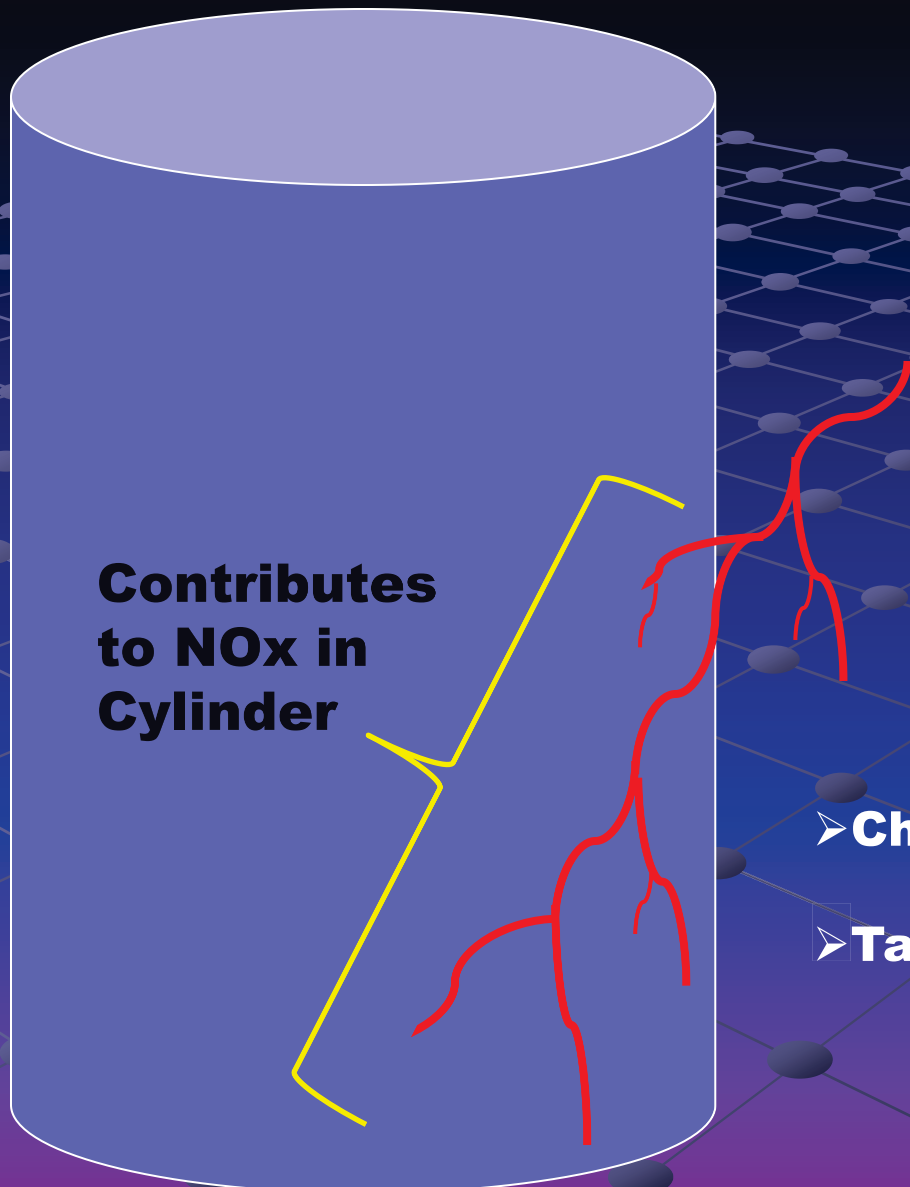
→More tortuosity
→Greater channel length
→More NOx

Sample Channel Lengths

(Aug 2006)



Computing Segment Altitude Distribution

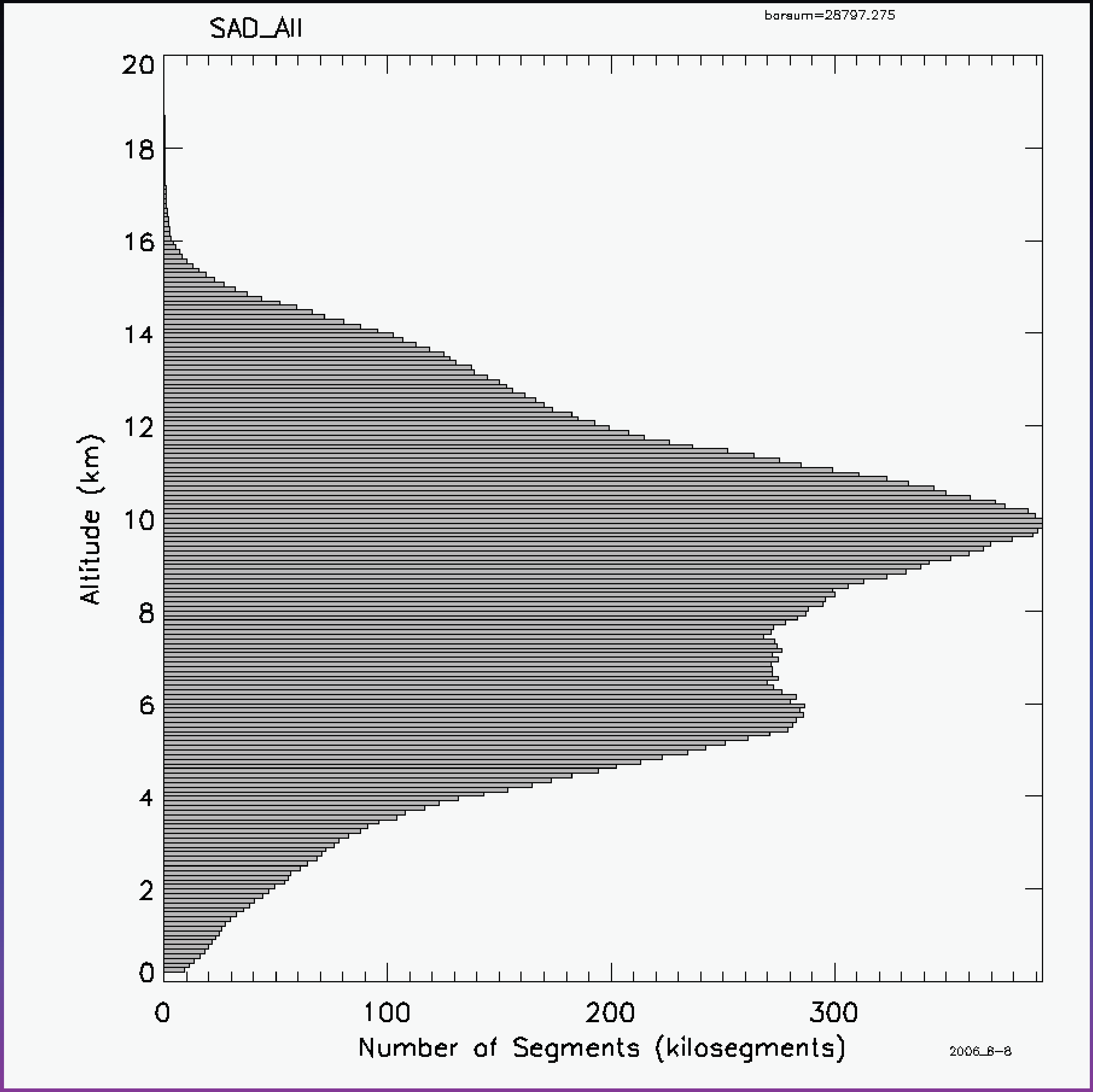


- Chop up Channel into 10-m Segments
- Tally segments in each 100 m layer (only within cylinder)

Sample SAD

[i.e., the 10-meter Channel Segment Altitude Distribution]

(Aug 2006)



Convert 10 m Segments to NOx

A. Yu-Jin Wang et al. (1998) Spark Chamber Results:

1. Return Stroke … is slightly more complicated than:

$$NO_x(I,h,m) = m\left[\, a + b\left|I\right| + cI^2 - B(p_o - p(h))\ \right]$$

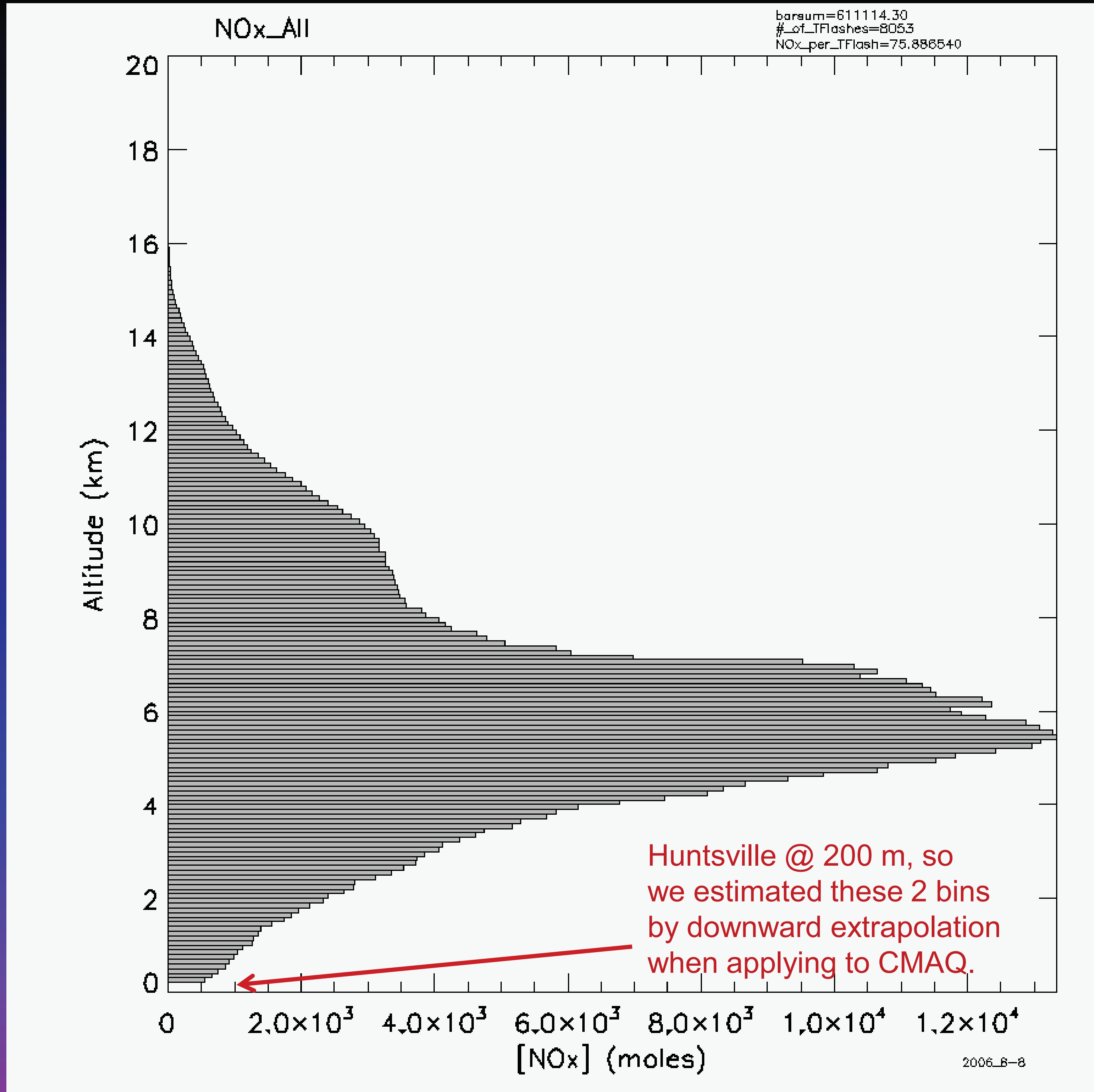
B. Cooray et al. (2009), but generalized for LNOM:

2. Hot Core of Stepped Leader
3. Corona Sheath of Stepped Leader
4. Hot Core of Dart Leader
5. K-Changes
6. M-Components
7. Continuing Current

… these last 6 depend on many variables: segment pressure, segment polar angle orientation, # K changes/segment, dart leader speed & current, stepped leader speed & current, continuing current speed & current, max path length from segment to a channel termination point, various production coefficients, fraction of ground flashes containing continuing currents, multiplicity.

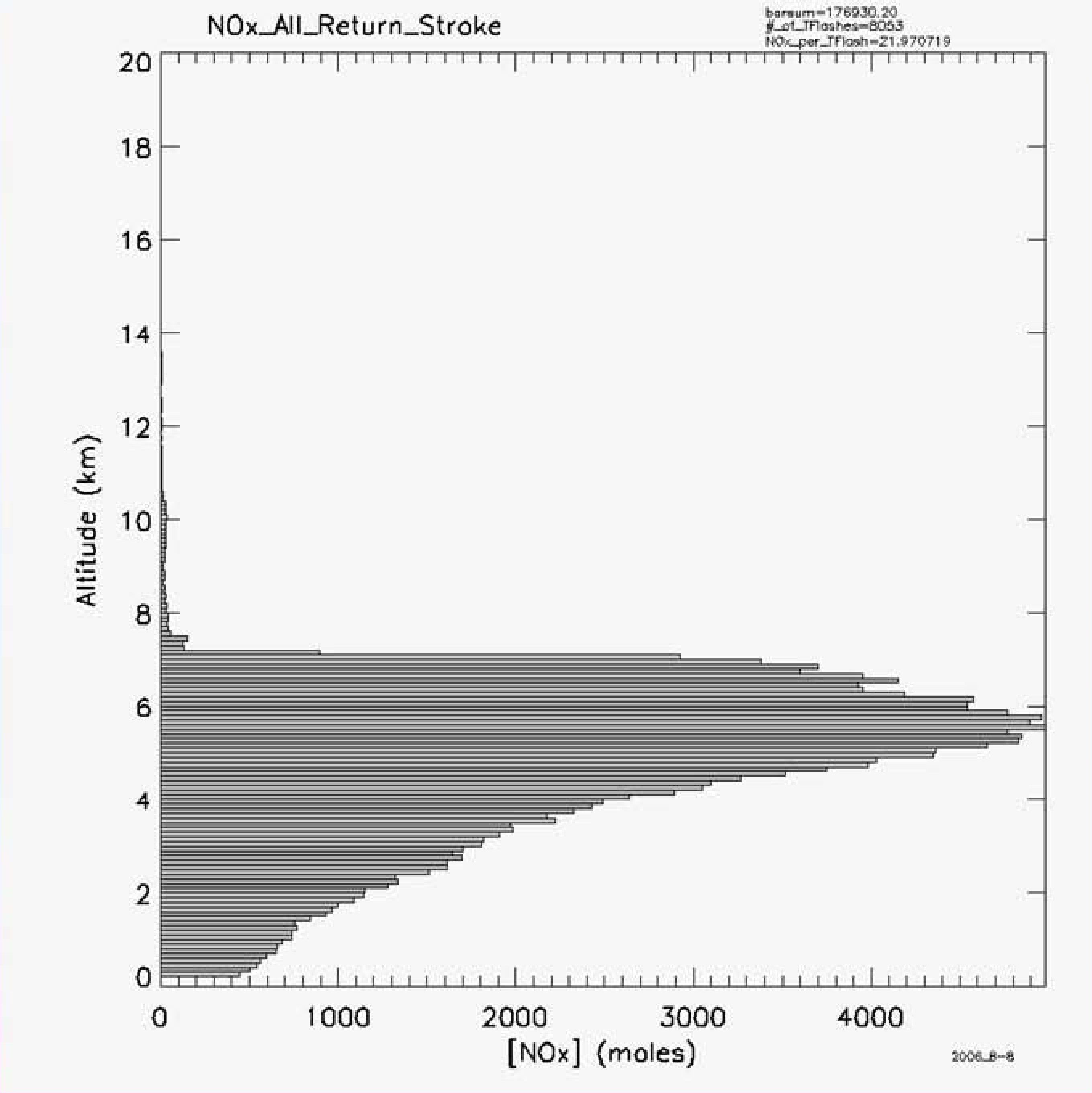
Sample NOx Profile

(Aug 2006)

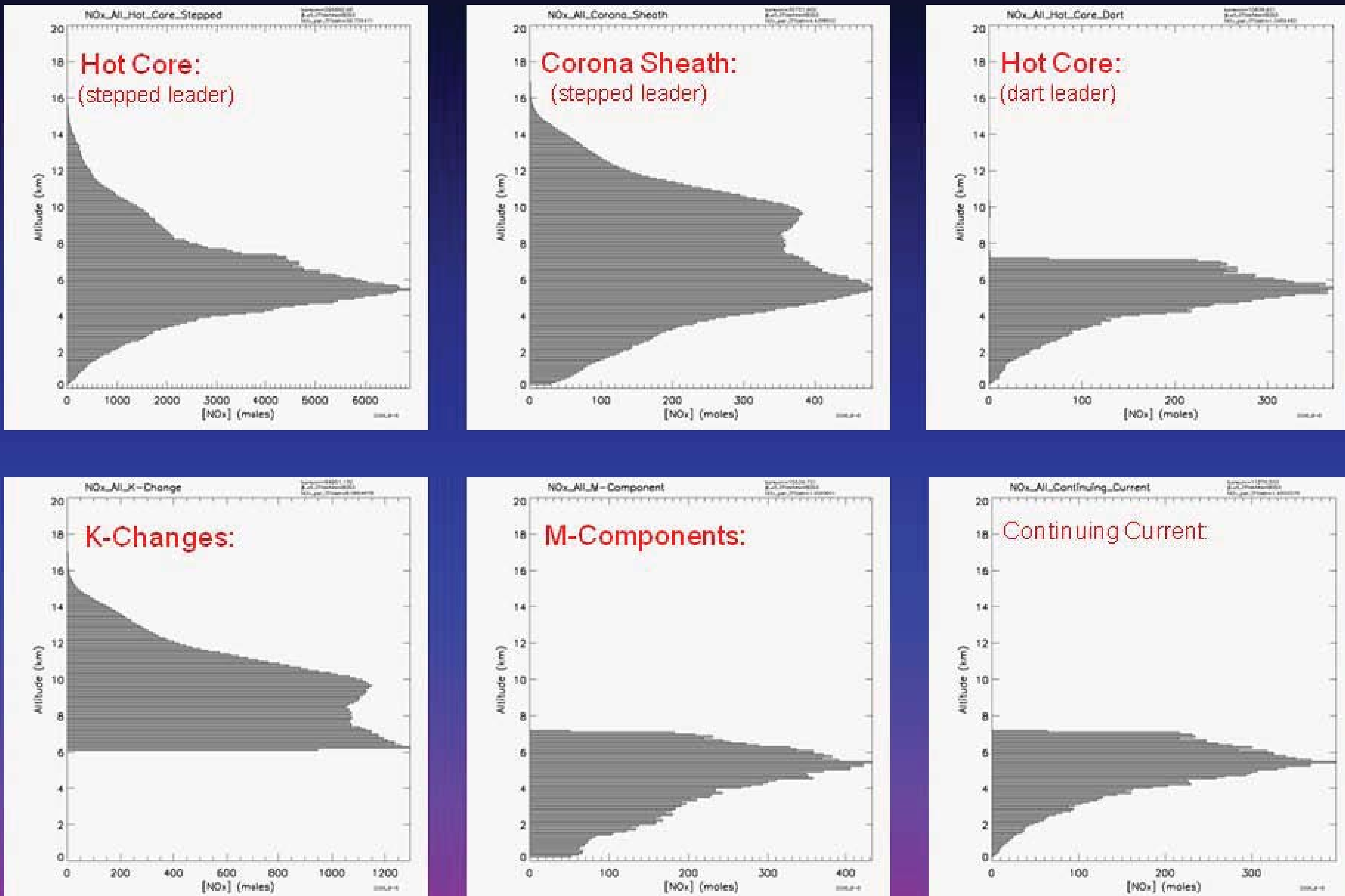


Return Stroke NOx Contribution

(Aug 2006)



Remaining NOx Contributions (Aug 2006)



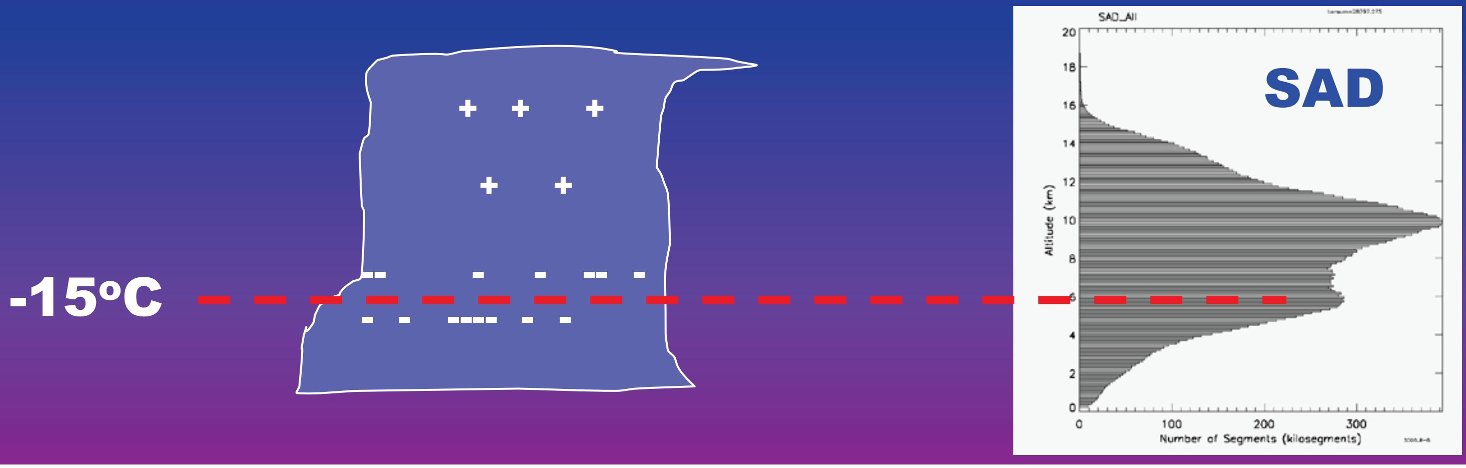
LNOM Analysis Summary Statistics

LNOM Lightning NOx ⟶ CMAQ

- **Ran LNOM on 5 Augusts: Aug 2005-2009** (27,873 flashes)
- **This gives (Ground, Cloud) Flash NOx Profiles**
- **Averaged the 5 Ground NOx Profiles** (gives an Aug estimate)
- **Averaged the 5 Cloud NOx Profiles** (gives an Aug estimate)
- **Convert NOx profiles to <u>NOx per flash profiles</u>**

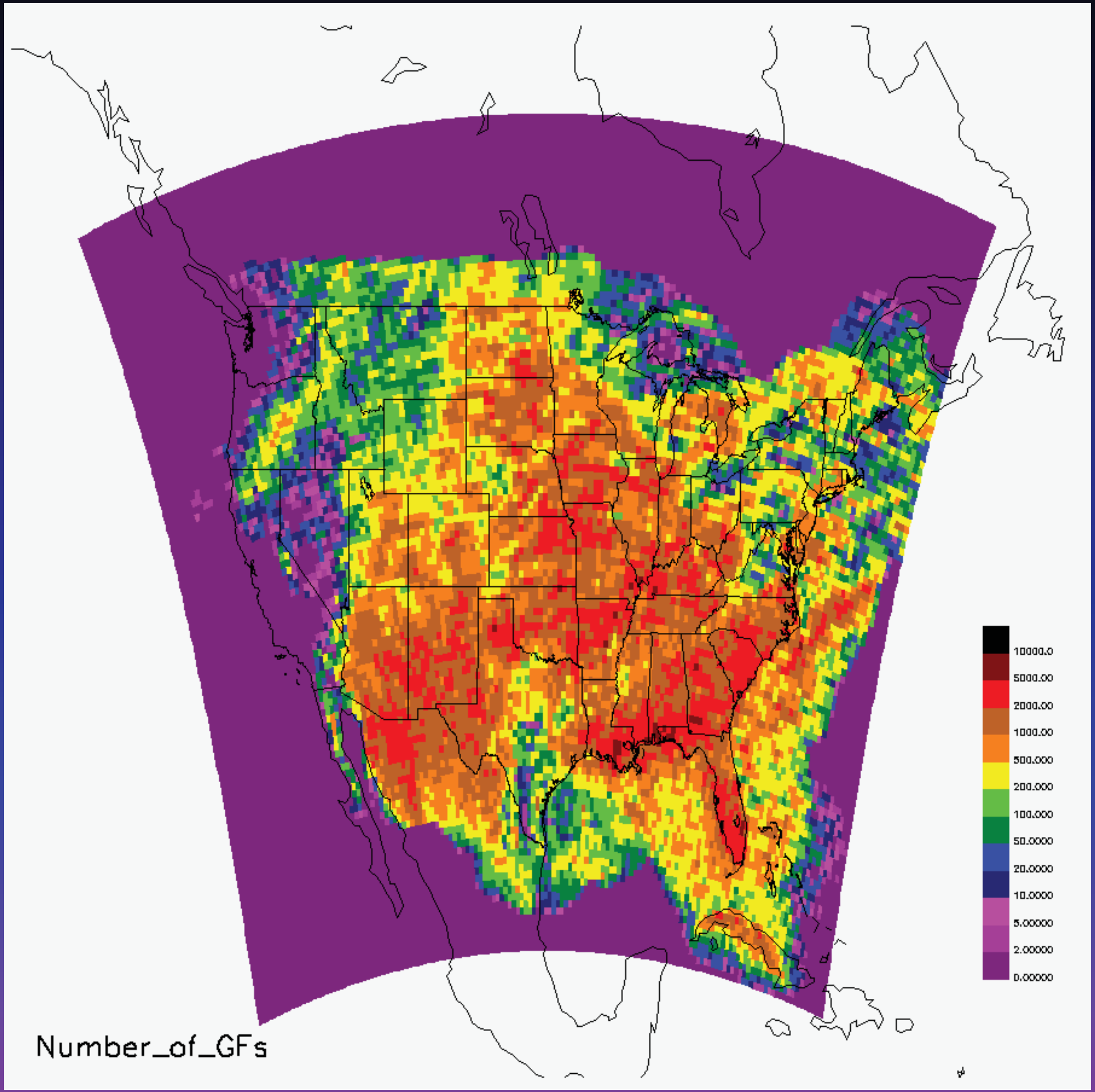
  (just divide by # of ground or cloud flashes analyzed)
- **Fill CMAQ Grid Cells with flashes** **(see next slide)**
- **Multiply <u>NOx per flash profiles</u> by # flashes in CMAQ cell to get NOx profile in cell;**

  N-Region has to be near -15^{o}C (Charging Zone):



Ground Flashes

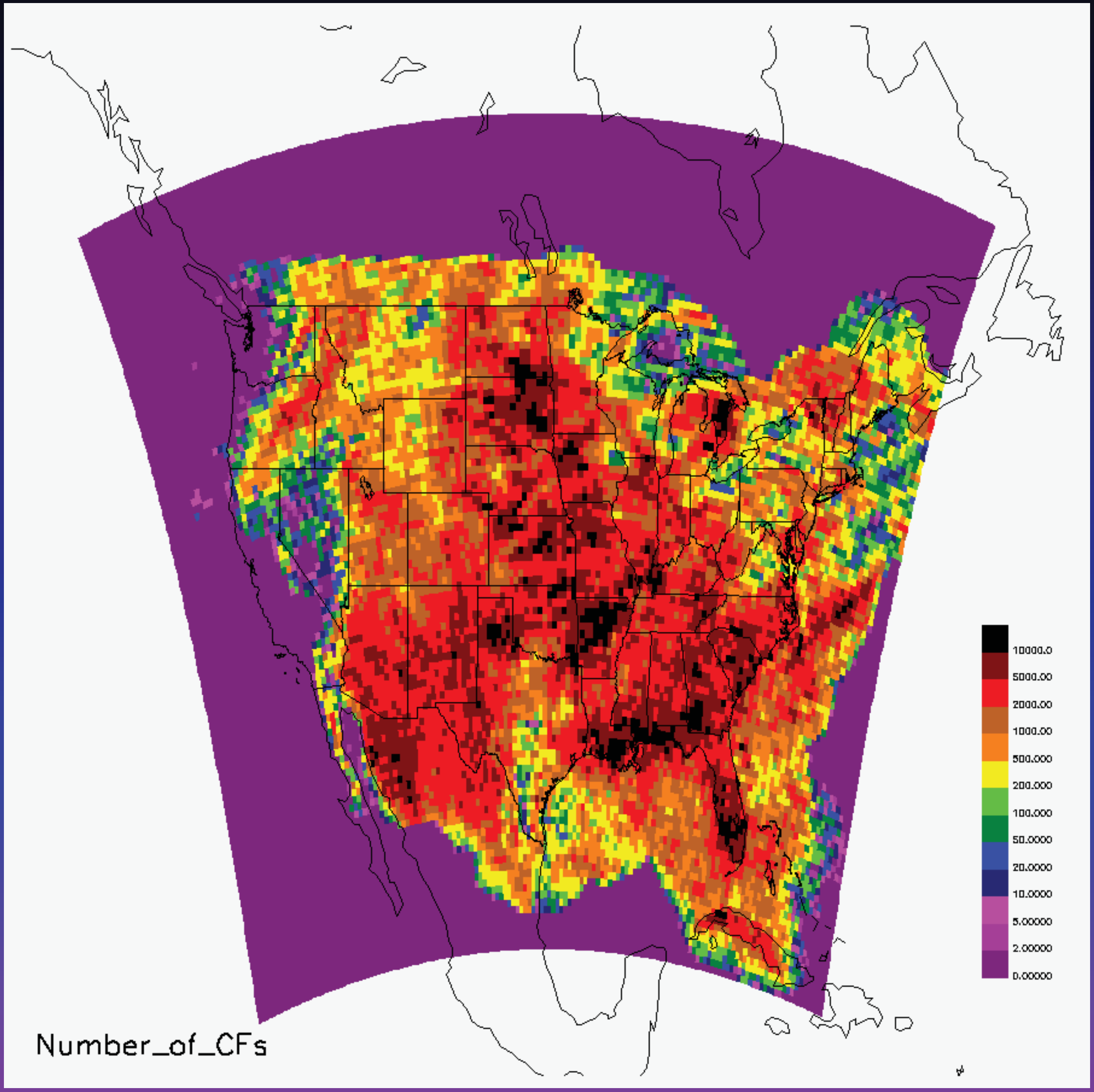
(Aug 2006)



Est. Cloud Flashes

$N_c = Z\ N_g$

(Aug 2006)



Impact on CMAQ Ozone Predictions…

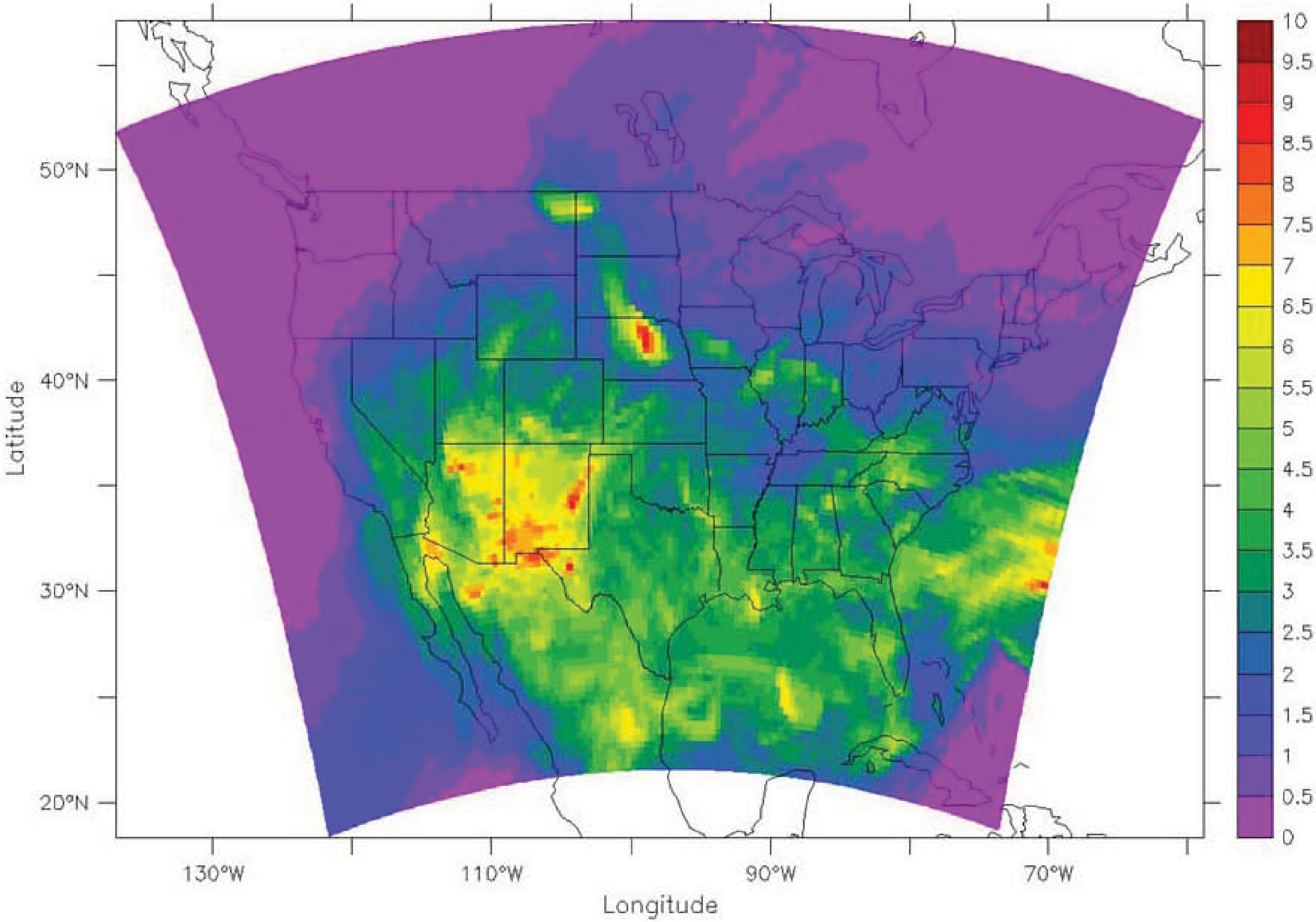


Figure 9. Maximum increase in surface O_3 due to lightning NOx (ppb).

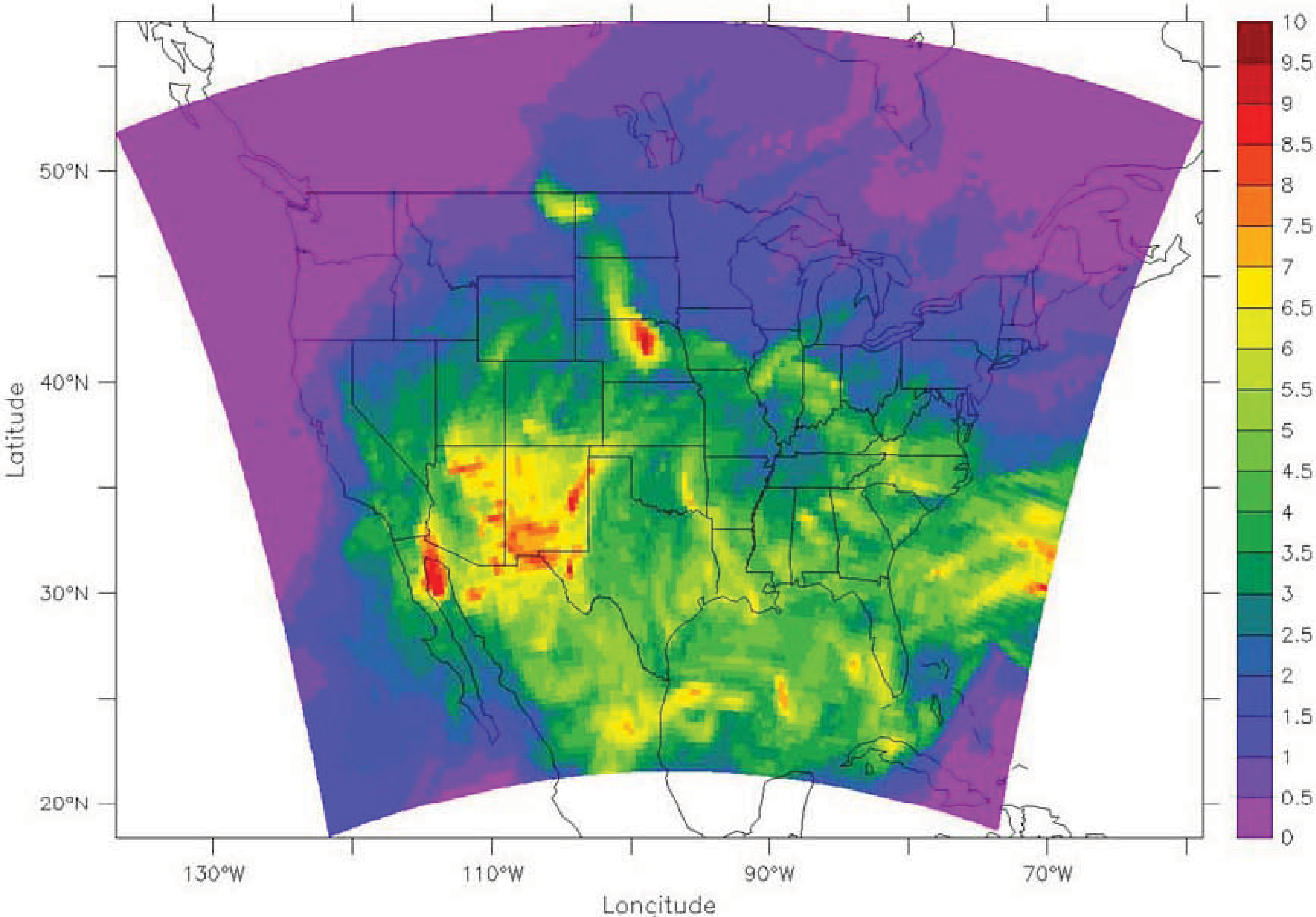


Figure 10. Maximum increase in boundary layer O_3 due to lightning NOx (ppb).

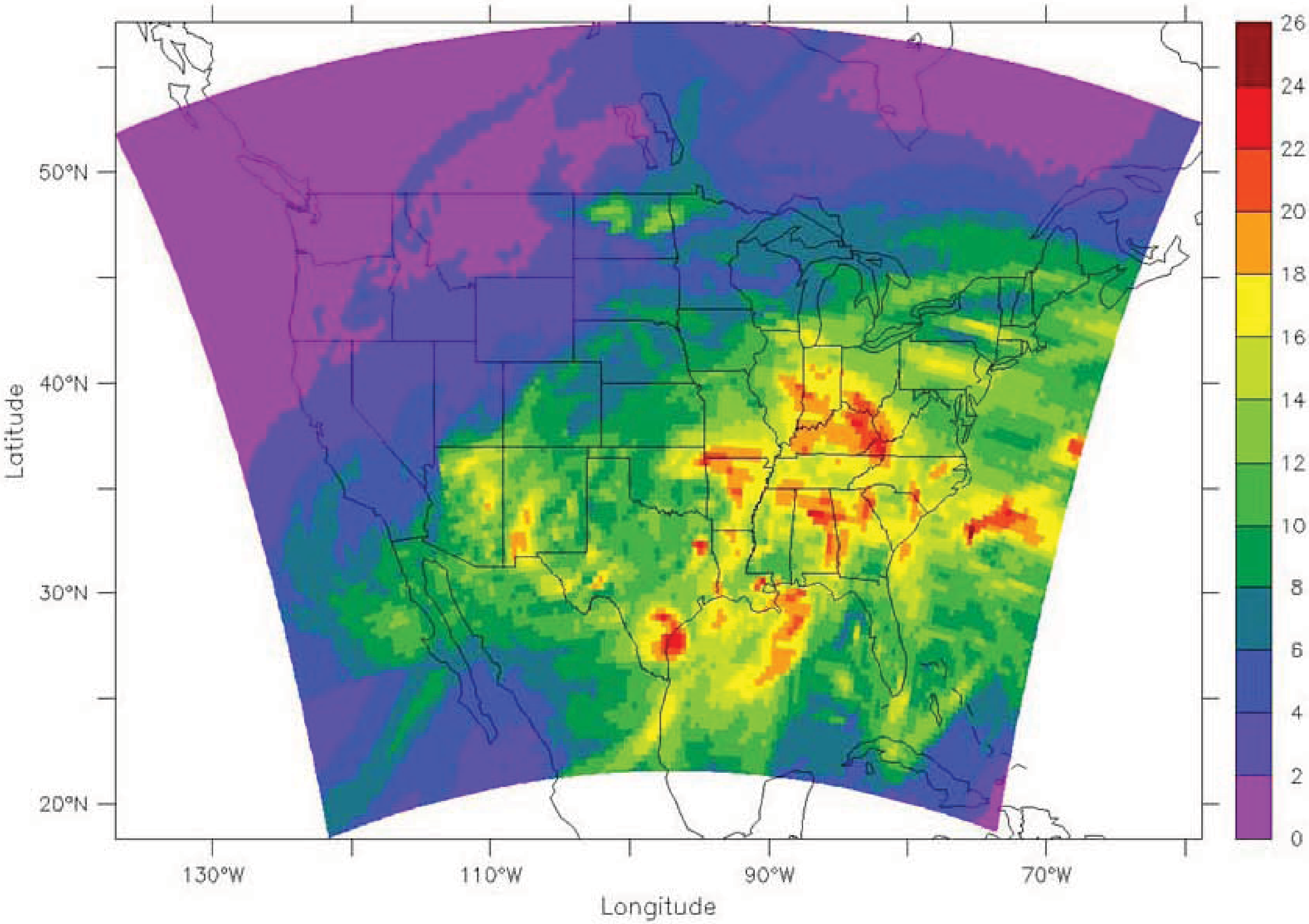


Figure 11. Maximum domain-wide increase in O_3 due to lightning NOx (ppb).

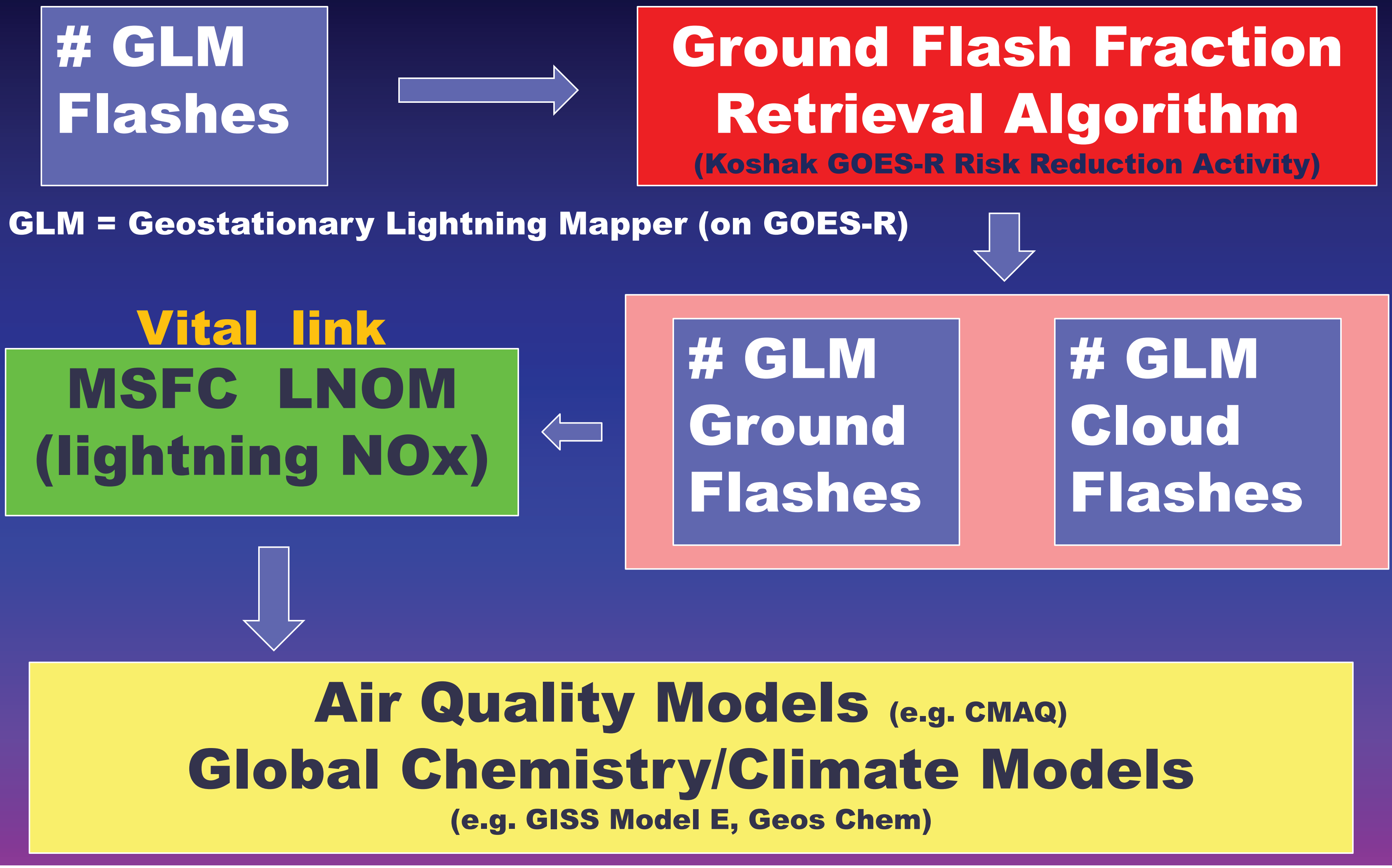
Summary of 2006 Analysis

- **LNOM provides most detailed "bottom-up" LNOx estimate:**
  - flash-by-flash analysis
  - specific channel geometry/height/length accounted for
  - Wang et al (1998) used to parameterize Return Stroke NOx production
  - Cooray et al (2009) used to parameterize 6 additional NOx producing processes
- **Latest LNOM NOx estimates show:**
  - Ground flashes produce ~ 14X more NOx than Cloud Flashes (not equal)
  - Ground flash NOx **~ 484 moles but varies!** (close to 250-500 mpf used by some)
  - Cloud flash NOx **~ 35 moles** (7 – 14X smaller than 250-500 mpf used by some)
- **Impact of LNOx on August 2006 CMAQ Run are Significant**

Most Important Upgrades in 2011

- **Feb 08:** Changed segment length from 1 to 10 m to improve LNOM speed.
- **Mar 09:** Changed nboxmin from 5 to 1, and scale from 1 km to 100 m to improve channel length computation.
- **Feb 23:** Height of N region computed using ave monthly sea-level temp (not SAD). Also updated leader current values.
- **Jun 23:** Added flash-specific output files.
- **Jul 15:** Improved flashtype subroutine to account for ambiguous flash types (V2/V3 nuances & 15 kA rule).
- **Aug 04:** Expand to any month (ave sea-level temps for all months in 2005-2010).
- **Aug 18:** Improved parameterization of +CG continuing currents (75% have, compared to only 30% of –CGs).
- **Aug 22:** Simplifying continuing current source to 100 ms duration.

Desired Future Application



More details on Ground Flash Fraction Retrieval

Koshak, W. J., Optical Characteristics of OTD Flashes and the Implications for Flash-Type Discrimination, J. Atmos. Oceanic Technol., 27, 1822-1838, 2010.

Koshak, W. J., R. J. Solakiewicz, Retrieving the Fraction of Ground Flashes from Satellite Lightning Imager Data Using CONUS-Based Optical Statistics, J. Atmos. Oceanic Technol., 28, 459-473, 2011.

Koshak, W. J., A Mixed Exponential Distribution Model for Retrieving Ground Flash Fraction from Satellite Lightning Imager Data, J. Atmos. Oceanic Technol., 28, 475-492, 2011.

Questions?